How Dim Accreting Black Holes Could Be?

Marek A. Abramowicz[1] and Igor V. Igumenshchev[2,3]

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge MA 02138

ABSTRACT

Recent hydrodynamical simulations of radiatively inefficient black hole accretion flows with low viscosity have demonstrated that these flows differ significantly from those described by an advection-dominated model. The black hole flows are advection-dominated only in their inner parts, but *convectively* dominated at radii $R \gtrsim 10^2 R_G$. In such flows, the radiative output comes mostly from the convection part, and the radiative efficiency is independent of accretion rate and equals $\epsilon_{BH} \simeq 10^{-3}$. This value gives a limit for how dim an accreting black hole could be. It agrees with recent *Chandra* observations which indicate that accreting black holes in low-mass X-ray binaries are by factor about 100 dimmer than neutron stars accreting with the same accretion rates.

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[1]Department of Astronomy & Astrophysics, Göteborg University & Chalmers University of Technology, 412-96 Göteborg, Sweden

[2]Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester NY 14623-1299.

[3]Institute of Astronomy, 48 Pyatnitskaya Ulitsa, 109017 Moscow, Russia.

1. Introduction

It was recognized already a long time ago that physics of the innermost parts of radiatively inefficient black hole accretion disks is dominated by advection (e.g. Abramowicz 1981; Gilham 1981; Begelman & Meier 1982). Advection-dominated accretion flow (ADAF) is a simple analytic model of such flows, constructed under the assumption that advection cooling dominates not only close to the black hole, but at all radii (Narayan & Yi 1994; Abramowicz et al. 1995). ADAFs provided a remarkably accurate *quantitative* prediction of detailed shapes of electromagnetic spectra of observed accreting black holes (see reviews in Narayan, Mahadevan & Quataert 1998; Kato, Fukue & Mineshige 1998). Perhaps, the most interesting prediction of the ADAF model, based *directly* on the existence of the black hole event horizon, is that for the same accretion rates, accreting black holes in compact binary systems should be considerably dimmer, than accreting neutron stars (Narayan & Yi 1995; Narayan, McClintock & Yi 1996; Narayan, Barret & McClintock 1997). That is simply because the advected energy is lost inside the event horizon of a black hole, while it is re-radiated from the surface of a neutron star. This prediction was recently confirmed by the *Chandra* data on soft X-ray transients in a low-luminosity quiescent state (Menou et al. 1999; Garcia et al. 2001). Specifically, it was found that accreting black holes are dimmer by the factor $f \simeq 100$ than neutron stars accreting at the same rates.

In this *Letter* we point out that the observed value of $f \simeq 100$ follows also from numerical models of radiatively inefficient accretion flows that have been recently constructed.

2. CDAFs versus ADAFs

Self-similar ADAFs are convectively unstable, as was demonstrated by Gilham (1981), Begelman & Meier (1982) and Narayan & Yi (1994). It was firmly established in several numerical works (Igumenshchev, Chen & Abramowicz 1996; Igumenshchev & Abramowicz 1999, 2000, 2001; Stone, Pringle & Begelman 1999) that the occurrence of this instability was not an artifact of simplifying assumptions adopted in self-similar ADAF models, but instead it is a genuine physical property of such flows with low viscosity (viscosity coefficient $\alpha \lesssim 0.1$). Note that the values $\alpha \lesssim 0.1$ is consistent with the present understanding of the origin of turbulent viscosity in accretion flows – it follows from simulations of the Balbus-Hawley instability (e.g. review in Hawley & Balbus 1995). Our recent numerical modeling of magneto-hydrodynamical (MHD) radiatively inefficient accretion flows (to be published) have shown that convection motions may develop in such flows. Results of these simulations clearly demonstrate close qualitative analogy between MHD and low viscosity hydrodynamical simulations of accretion flows. In subsequent publications we shall discuss in details our MHD simulations, and in particular explain why results of any realistic MHD simulations *should* differ from those recently reported by Hawley, Balbus & Stone (2001).

Thus, according to present understanding of turbulent viscosity in accretion flows and estimates of its magnitude, radiatively inefficient accretion flows *must be* convective. Convection is not a small perturbation to ADAFs, instead it significantly changes the radial structure of such flows. With respect to ADAFs (with $\rho \propto R^{-3/2}$), the convection-dominated accretion flows (CDAFs) have a much flatter radial density profile, $\rho \propto R^{-1/2}$, and reduced mass accretion rates. Convection carries angular momentum radially inwards and energy outwards. Simple analytic self-similar models of CDAFs which reproduce all these properties and reasonably agree with numerical models have been constructed by Narayan, Igumenshchev & Abramowicz (2000) and Quataert & Gruzinov (2000). An analysis of self-similar CDAFs have shown that the radiatively inefficient accretion flows are advection-dominated in the inner part ($R \lesssim 100 R_G$) and convection-dominated in the outer part (Abramowicz et al. 2001). However, the presence of the relatively small inner advection-dominated part in such flows makes very little change to their global structure well described by the CDAF model.

For the present discussion of how dim accreting black holes could be, it is important to note that CDAFs have a significant (with respect to ADAFs) outward energy flux carried by convection, with the "luminosity" $L_c = \epsilon_c \dot{M} c^2$, where $\dot{M}$ is the mass accretion rate, and ϵ_c is the "efficiency". From numerically constructed hydrodynamical models one concludes that $\epsilon_c \approx 3 \times 10^{-3} - 10^{-2}$ and weakly depends on parameters of the problem, which are the adiabatic index γ and the viscosity parameter α. The value of ϵ_c is independent of the accretion rate. CDAFs radiate mostly at their outer parts due to the flattened density profile (Igumenshchev 2000; Igumenshchev &

Abramowicz 2000). Ball, Narayan & Quataert (2001) have studied radiative processes that will transform a fraction η of the outward convection energy flux into radiation. They have concluded that the most important radiative process is bremsstrahlung and most of the energy is radiated in X-rays. They pointed out that although at present one could give only a very rough estimate for η, because of purely known conditions in accretion flows on outside, it is unlikely that η is significantly smaller than 1. In this *Letter* we assume that $\eta \simeq 0.1 - 1$.

We conclude, based on the given above arguments, that the radiative output of radiatively inefficient black hole accretion flows is determined by the convection part of the flow. It peaks at X-ray frequencies and has the radiative efficiency $\epsilon_{BH} = \eta \epsilon_c \simeq 10^{-3}$.

Note that our estimate of ϵ_{BH} is based on the assumption of negligible heating of electrons during the viscous dissipation of rotational and gravitational energies in accretion flows. If electrons are heated more significantly through magnetic reconnections, as Bisnovatyi-Kogan & Lovelace (1997) argued, the value of ϵ_{BH} could be much larger. However, there is no robust theoretical estimates of importance of this effect (Quataert & Gruzinov 1999).

3. Discussion and conclusion

Narayan's prediction that the event horizon makes radiatively inefficient black hole flows much dimmer that neutron star flows at the same accretion rates was confirmed by the *Chandra* data (Menou et al. 1999; Garcia et al. 2001). These authors (and Lasota 2000) have convincingly argued that the observed X-ray luminosities come from accretion power, and therefore the observed difference – black holes are about 100 times dimmer than neutron stars – should be explained by difference in radiative efficiency of accretion flows. We point out that for neutron stars the efficiency has its standard value $\epsilon_{NS} \approx 10^{-1}$ (e.g. Frank, King & Raine 1992), and therefore the factorial difference in luminosities $f = \epsilon_{NS}/\epsilon_{BH} \simeq 100$ as indeed observed.

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